

POTENTIAL OF EVAPORATIVE COOLING SYSTEMS FOR BUILDINGS IN INDIA

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ABSTRACT

Evaporative cooling potential for building in various climatic zones in India is investigated. Maintainable indoor conditions are obtained from the load – capacity analysis for the prevailing ambient conditions. For the assumed activity level, clothing and air velocity, the predicted mean vote (PMV), predicted percentage dissatisfied (PPD), and cumulative dissatisfaction levels for each month are estimated.

Time – air condition contours of ambient, supply air and indoor air are plotted on a psychrometric chart for different cities in India like Ahmadabad, Jodhpur, Nagpur and New Delhi representing different climatic conditions of India. While satisfactorily comfort can be achieved at cool and dry weather conditions by evaporative cooling system throughout the year, some discomfort prevailed for few months around July at hot and dry/humid weather conditions. The results are also quantified in terms of PMV, PPD and their cumulative factors; PMV-hour and PPD-hour.

INTRODUCTION

Thermal comfort is a desired feature of human life. It also enhances the productivity in general. But air conditioning is an energy intensive process. Depending on type and size of the building, about 40 to 70 % of the total energy consumption will be by the air conditioning system. Evaporative cooling is cheaper but its performance and efficiency depend on the prevailing weather conditions. Hence perfect comfort conditions in the building cannot be guaranteed.

The comfort zone for evaporative cooling lies between 20 and 80% relative humidity (RH) curves on the psychrometric chart. The central axis of the zone representing comfort for people is 23.9°C effective temperature line. At higher air velocities, higher effective temperature is acceptable. As compared to vapour compression cooling, in evaporative cooling the air velocities in the room can be higher. One authority recommends between 0.5 to 1.0 m/s. In fact 1.5 m/s is not unusual. A study with air velocities ranging from 0.46 to 1.12 m/s found that perfect comfort condition prevailed at the highest

value of air velocity and aroused no occupant objections. Evaporative cooling does not give perfect comfort conditions in space and some sacrifice in terms of air velocity, dry bulb temperature (DBT) and relative humidity (RH) has to be made. The performance of evaporative cooler depends on ambient conditions but it is less expensive to operate than the mechanical cooling system.

In this paper comfort conditions in evaporatively cooled building at many locations is predicted using comfort indicators such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). The level of comfort achieved in a standard office building in dry-hot climate during day time, using roof evaporation modified cooling tower model is studied. The roof is assumed to be without any insulation. The result is quantified in terms of comfort indicators.

Thermal Comfort

Factors affecting the thermal comfort are air temperatures, mean radiant temperature, humidity, air speed, metabolic rate and clothing levels. The air temperature is the equilibrium dry-bulb temperature (DBT) attained by the space, so is the humidity. Air speed in our case should be zero or a low value. A clothing level of 0.6 Clo is assumed which is about the average clothing in hot Indian climate in an office environment.

The rate at which body produces heat is called the metabolic rate. The heat produced by a normal healthy sedentary person is called the basal metabolic rate and is of the order of 58 W/m² (1 met). The maximum value may be as much as 8 times of this for a person engaged in sustained hard work. For our model a value of 65 W/m² is assumed.

Human comfort ultimately is influenced by physiological factors determined by the rate of heat generation within the body and the rate of heat dissipation to the environment. PMV is a standard psycho physical scale for a large group of persons. It incorporates the influence of activity, clothing, air temperature, mean radiant temperature, relative air velocity and air humidity. PMV values range from

minus 3.0 (cold) to plus 3.0 (hot) with zero as the neutral sensation representing the most comfortable condition.

PPD is the percentage of a large group of people that can be expected to feel definitely uncomfortable in a given environment. PPD is a semi-logarithmic plot of the total percentage dissatisfied as a function of the PMV and is a more meaningful index in rating the quality of the indoor climate as it is the decidedly dissatisfied who will be inclined to complain. It may be noted that a PMV of magnitude less than 1.0 is regarded as practically comfortable. The corresponding PPD is 26.15. Both PMV and PPD are non dimensional quantities.

In order to correlate the intensity and duration of comfort indicators, a comprehensive indicator “total discomfort” has been evaluated. It is an integration of the PMV or PPD curve over time for which discomfort is felt. Thus, $PMV > 1.0$ is accounted for and corresponding $PPD > 26.15$ is accounted for in the total discomfort. This very well illustrates that moderate discomfort for a long duration can be as uncomfortable as severe discomfort for a shorter duration.

MODEL AND MEHOD OF SOLUTION

The evaporative cooling model used for the study is shown in Figure 1. It consists of a modified cooling tower with tower inlet-exit HX. Water cooled in the cooling tower is passed through a saturation pad where direct evaporative cooling occurs thus reducing the dry bulb temperature of the air. This air is then supplied to the room. The supply air picks up the various loads in the space and equivalent amount of space air is exhausted to the ambience.

Evaporative cooling is also used at the roof as modeled in Figure 2. A thin film of water present on the roof surface reduces the heat load transmitted through the roof to the space. However no insulation is considered for the roof. Heat transfer through the evaporative cooled roof is unsteady and one dimensional with periodic boundary conditions. The exposed roof surface reflects a part of incident solar radiation. The absorbed part heats the surface. Sky radiation and evaporative heat transfer take place from the surface to ambient. The remaining heat conducts through the layers of the roof, enroute getting stored partially. The heat which finally convects to the room manifests as cooling load. Transmission heat gain through the building fabric is estimated by CLTD-CLF method [ASHRAE (1989)] except for the roof. Internal sensible and latent heat generations by occupants, lighting, appliances, etc.

are specified. The overall cooling load is estimated as a function of indoor temperature for a representative day of each month.

Psychrometric, energy, mass and material equations are used in the modeling the evaporatively cooled building. An established procedure is adopted to model counter flow cooling tower (Figure 3). Cooling capacity of the overall evaporative system is estimated as a function of indoor temperature for a representative day of each month. Solving this together with that of the load mentioned above provides both indoor temperature and cooling load/capacity.

The thermal load on the body, L , defined as the difference between the internal heat production and the heat loss to the actual environment is given by,

$$L = (M - W) = 3.96 \times 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_{rm} + 273)^4] + f_{cl} h_c (t_{cl} - t_a) + 3.05 [5.73 - 0.007 (M - W) - p_a] + 0.42 [(M - W) - 58.15] + 0.0173 M (5.87 - p_a) + 0.0014 M (34 - t_a) \quad (1)$$

where, M = metabolic heat production, W/m^2
 W = external work accomplished, W/m^2
 f_{cl} = clothing area factor, dimensionless
 t_{cl} = clothing surface temperature, $^{\circ}C$
 t_{rm} = mean radiant temperature, $^{\circ}C$
 p_a = water vapour pressure in air, kPa

The predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) are given by,

$$PMV = [0.0303 \exp(-0.036M) + 0.028] L \quad (2)$$

$$PPD = (100 - 95) \exp[-(0.03353) PMV^4 + 0.2179 PMV^2] \quad (3)$$

Total discomfort

$$DISCOMFORT = \int_{time} PMV dt \text{ for } PMV > 1.0 \quad (4)$$

Unit is PMV- hours. Total discomfort can also be calculated with PPD as the base. Then PPD values greater than 26.15% only are taken in account.

Various operating parameters like NTU, m_w , m_a , m_s , E1, E2 and E3 are assumed. The location of the building / city (longitude, latitude and altitude) is known. Hourly variations of DBT, RH, air velocity and global radiation in a representation day of the chosen month are obtained from Mani (1980). The

building size and constructional details (k , ρ , C_r , X , h_{ci} , h_{co} , α and ε of roof, and other relevant details to calculate transmission and fenestration loads from wall and window by CLTD-CLF method [ASHRAE (1989)], Q_{si} and Q_{li} are assumed. The equilibrium space temperature and humidity along with the associated comfort parameters are then found for a representative day of each month. The thermal load on the body (L) and the two comfort indices namely PMV and PPD are calculated using Eqs. (1), (2) and (3) respectively. The PMV value is checked and added to DISCOMFORT value if it is greater than 1.0 as per Eq. (4) and similarly for PPD based total discomfort is estimated.

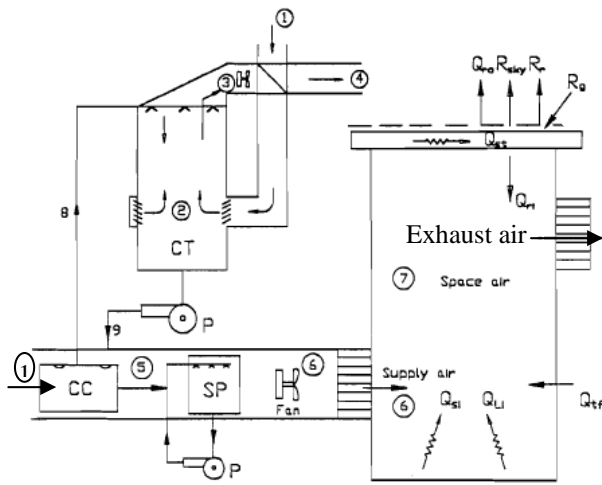


Figure 1. Model of evaporatively cooled space

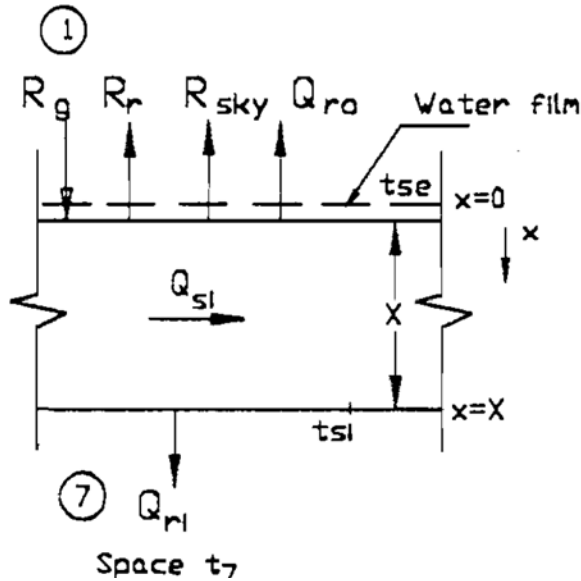


Figure 2. Analytical model for roof heat

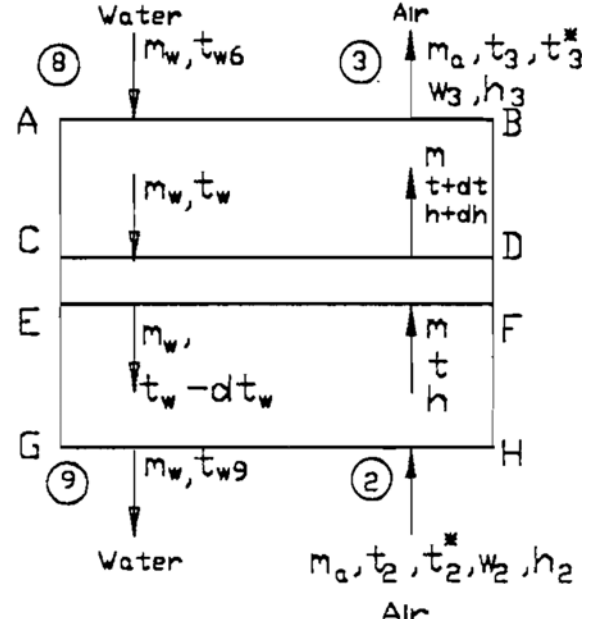


Figure 3. Model of counter flow cooling

RESULTS AND DISCUSSIONS

The indices PMV-Hours and PPD-Hours (PMV is predicted mean vote and PPD is predicted percentage dissatisfied) have been chosen to illustrate the effect of uncomfortable conditions prevailing over a period of time. PMV-Hours for a day includes the sum total of PMVs integrated over time that exceeds the specified comfort range. Thus PMV exceeding value of one is included in discomfort index PMV-Hours. The corresponding value of PPD is 26.15%.

Parameters and Range

Parametric study is carried out for a single storey building in hot and dry climate situated in the five cities of Jodhpur, Ahmadabad, Nagpur, New Delhi and Bangalore. The building dimensions are 50 m long, 25 m wide and 10 m high. It is oriented towards north. The walls are light coloured, sunlit and 'type D' [ASHRAE (1989)] with overall heat transfer coefficient equal to $2.344 \times 10^{-3} \text{ kW}/(\text{m}^2 \text{ K})$. Windows are shaded with shading coefficient equal to 0.7 and overall heat transfer coefficient equal to $6.0 \times 10^{-3} \text{ kW}/(\text{m}^2 \text{ K})$. The four façade areas are equally divided between walls and windows. Roof is 0.125 m thick concrete with $k = 1.5 \times 10^{-3} \text{ kW}/(\text{m K})$, $C_p = 0.9 \text{ kJ}/(\text{kg K})$, $\rho = 2240 \text{ kg}/\text{m}^3$, $h_{ci} = 6.25 \times 10^{-3} \text{ kW}/(\text{m}^2 \text{ K})$, $\alpha = 0.65$ and $\varepsilon = 0.85$.

The study is carried out for all the months of the year with a constant evaporative cooled water flow rate (m_w) of 10 kg/s. The ranges of the variable parameters are listed in Table 1.

Table 1. Variable parameters and ranges

Sl.#	Parameter	Symbol	unit	Range			
				1	2	3*	4
1	Number of transfer unit	NTU	ND	0.5	1	2	4
2	Cooling tower air flow rate	ma	kg/s	5	10	20	40
3	Supply air flow rate	ms	kg/s	10	20	30	40
4	Efficiency of tower heat exchanger	E1	ND	0	0.5	0.75	1
5	Efficiency of cooling coil	E2	ND	0	0.5	0.75	1
6	Efficiency of cooling pad	E3	ND	0	0.5	0.75	1
7	Internal sensible heat	Qsi	kW	50	75	100	125

* Mean values

The mean value selected for each parameter is most practical and widely accepted [ASHRAE (2003)]. The ranges are also more or less practicable and these values are selected judiciously to clearly bring out their effect on thermal performance of the building. Each one of these inter linked variable parameter is varied keeping the others at their respective mean values. The results so obtained are presented in Figures 4, 5 and 6.

Cooling Tower

Size (NTU) and heat exchanger effectiveness (E1) are the two important parameters of the modified cooling tower. The influence of these two on discomfort for both PMV-Hours and PPD-Hours is depicted in Figures 4a and 5a, and Figures 4b and 5b respectively for New Delhi. Larger the cooling tower (higher NTU), better will be the cooling of water. Hence supply air can be cooled better in the cooling coil and consequently low space temperature can be obtained. Hence lower values of PMV and PPD can be obtained. Effectiveness $E1 = 0$ corresponds to standard cooling tower, i.e. without the air to air heat exchanger. At high effectiveness, air entering the cooling tower would be sensibly cooled to a large extent in the heat exchanger thus significantly reducing its wet bulb temperature. Modified cooling tower adopts this concept to get water at temperature sometimes lower than that of ambient wet bulb temperature itself. Hence with high heat exchanger effectiveness, better comfort can be obtained.

Significance of efficient cooling coil in providing comfort conditions in space by evaporative air cooling is depicted in Figures 4c and 5c. As the coil efficiency (E2) increases, better sensible cooling of air takes place. Thus high efficiency helps in

providing low space temperature but with marginally high space humidity. The relevant curve of efficiency $E2=0$ in the figures corresponds to what is called 'direct evaporative air cooling' or space cooling by 'desert cooler' with cooling pad efficiency, $E3 = 0.75$.

Saturation pad cools the air adiabatically keeping the air wet bulb temperature constant. Role of such as a pad in the final stage of cooling of supply air is shown in Figures 4d and 5d. The comfort level is positively influenced by efficiency of saturation pad. Higher the efficiency better is the achieved comfort level. It is interesting to note that modified cooling tower with $E3 = 0$ corresponds to cooling of space by only the conventional 'indirect evaporative cooler'.

Supply Air

The role of flow rate of evaporatively cooled supply air in maintaining comfort conditions in space is shown in Figures 4e and 5e. ASHRAE (2003) recommends supply air flow rate in the range of 12 to 30 kg/s for the chosen building with conventional air conditioning system. Higher supply air flow rate is permitted for evaporative air cooling of the building [Watt (1986)]. The figures illustrate the advantage of high supply air flow rate in maintaining comfort conditions but it follows the 'law of diminishing return'. The cooling potential of higher supply rate is due to its larger heat absorbing capacity.

Internal Heat

The lighting, normal equipment and electrical loads range from 20 to 50 W/m² of floor area in a typical office building [ASHRAE (2003)]. For the chosen building this corresponds to 50 to 125 kW and the internal load is varied in this range as shown in Figures 4f and 5f. It is quite evident that high internal sensible load increases discomfort in space. The figures also reveal the linear relationship between the internal sensible load and the two comfort indices.

Indoor Conditions

Figure 6 shows the contours of ambient conditions (State 1), conditions of air after passed through cooling coil (State 5), supply air (State 6) and maintainable space conditions (State 7) from 7 to 20 hours on the psychrometric chart for different cities namely Jodhpur, New Delhi, Nagpur and Ahmadabad in the month of June. The individual variation is more or less similar in all the plots. As time progress, the evaporative air cooling system provides better comfort cooling even though ambient Dry bulb temperature increases. This is essentially due to the facts that, as time progresses, (i) relative humidity of ambient air decreases and (ii) there exists more scope for sensible cooling in tower HX.

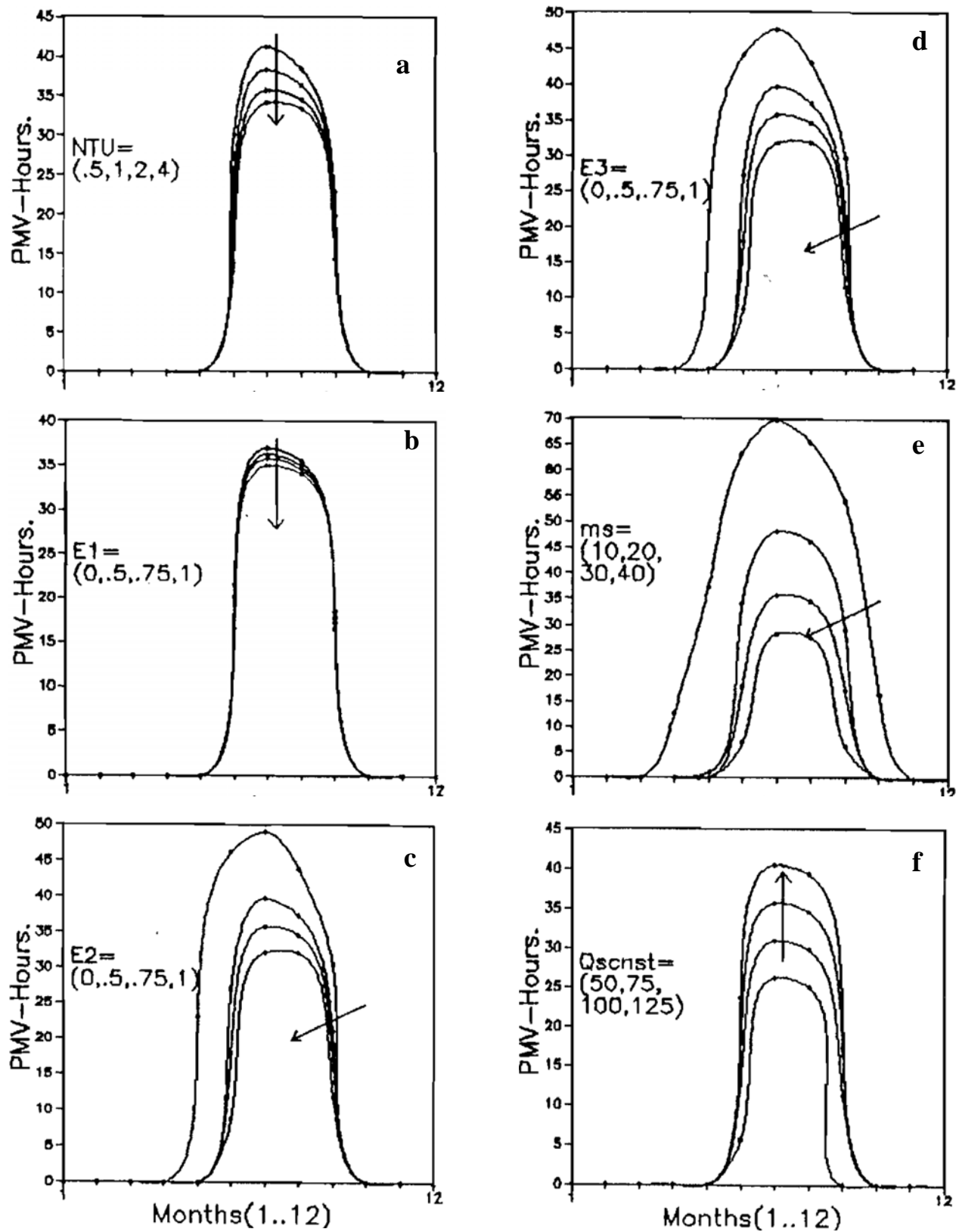


Figure 4. Influence of various operating parameters on PMV - Hours at Jodhpur at different months

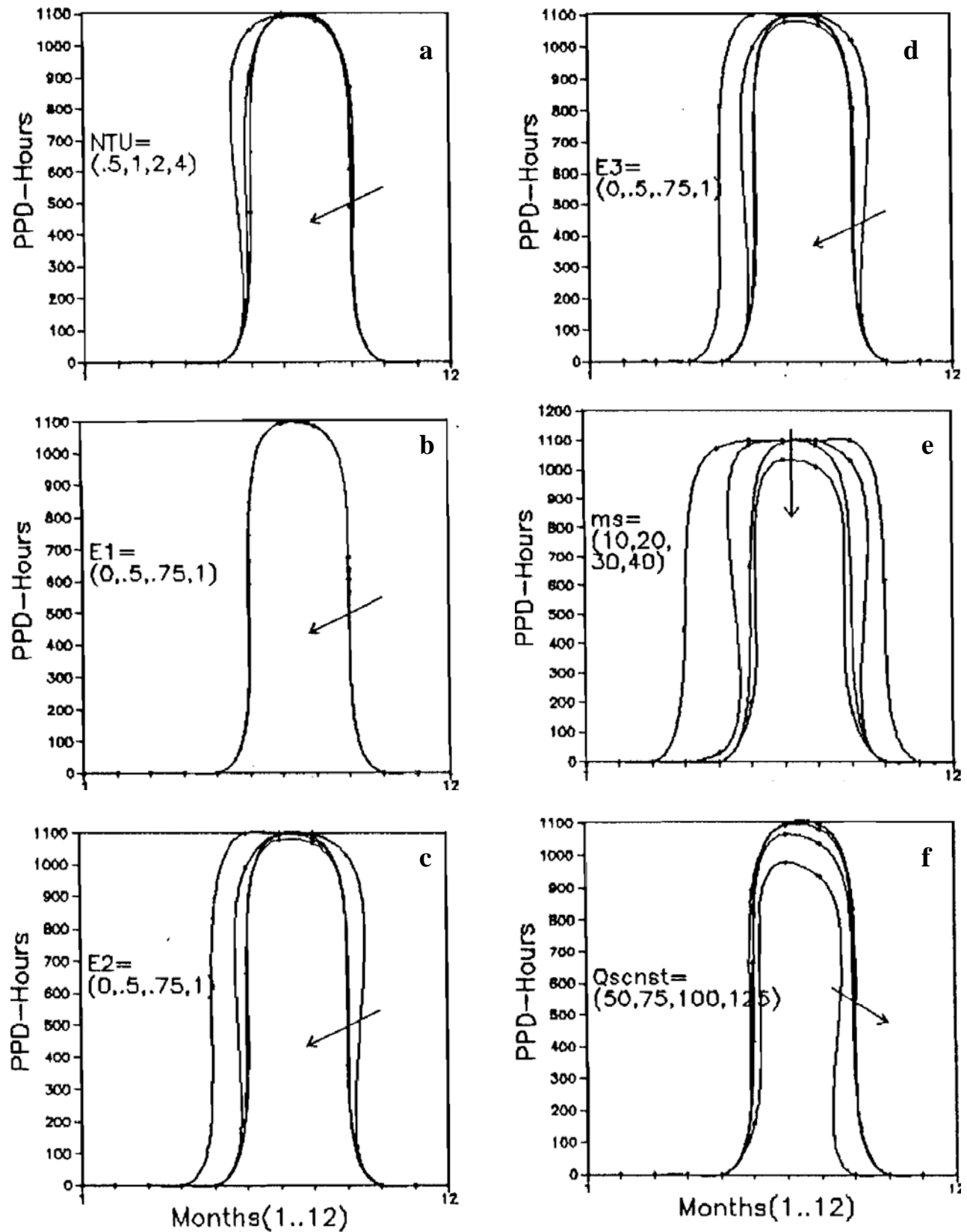


Figure 5. Influence of various operating parameters on PPD – Hours at Jodhpur at different months

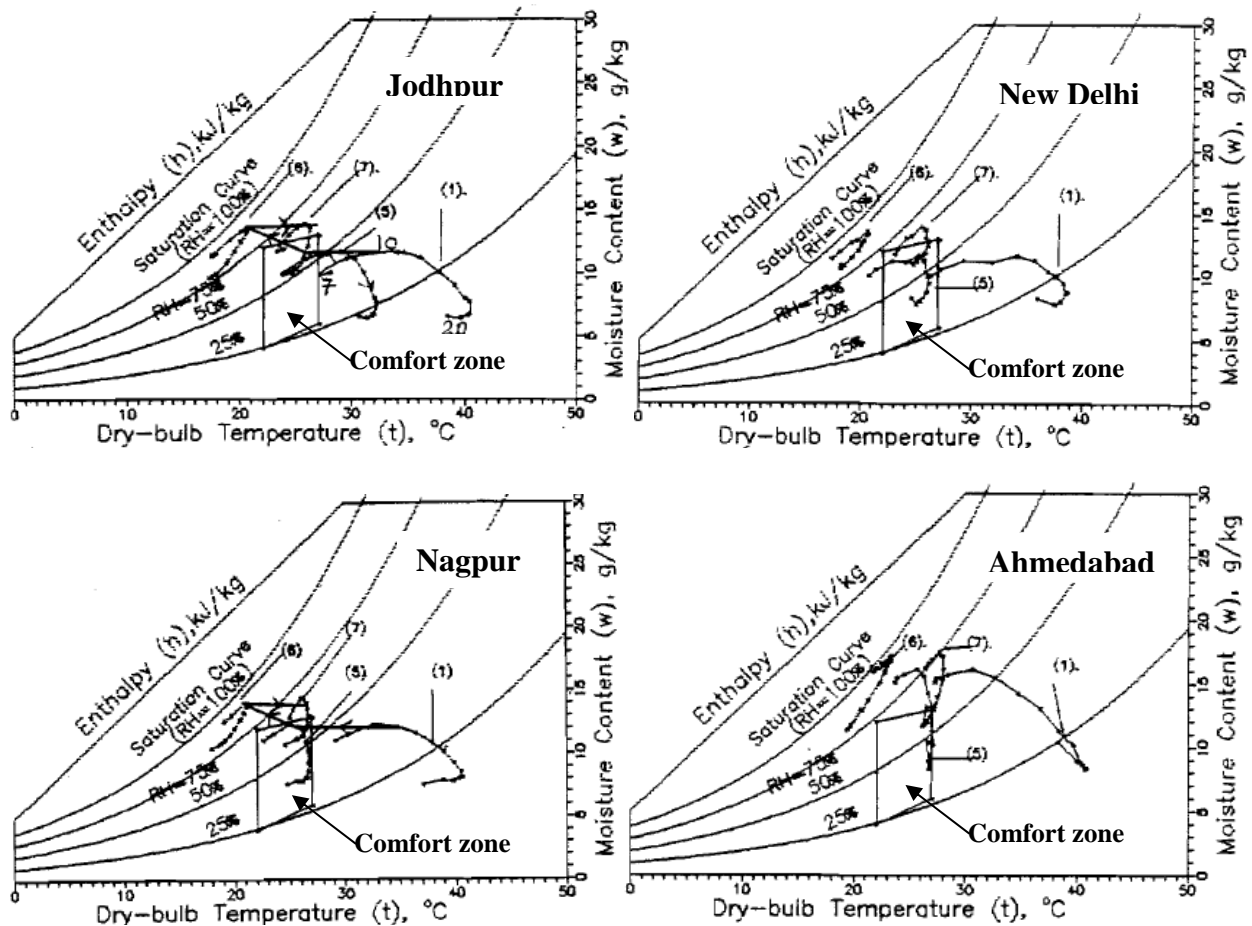


Figure 6. Plots of various states of air in the model for four cities in the month of June. State (1) Ambient air, State (5) Air after having passed through cooling coil, State (6) Air after saturation pad (Supply air) and State (7) Space condition

Figure 6 shows that maintainable comfort conditions vary depending on the climatic conditions. ASHRAE comfort zone is also superimposed in the figure. The maintainable conditions are either within the comfort zone or in the vicinity of it during afternoon hours. Ahmadabad is a difficult city due to higher humidity than Jodhpur, though ambient temperature in the latter is much higher.

CONCLUSIONS

A typical building with provision for roof evaporative cooling is modeled predicting the maintainable indoor conditions at different cities representing different climatic zones in India. Psychrometric, property data heat and mass transfer / balance, etc. equations are used for the modeling. The study reveals that centralised evaporative air cooling is feasible for human comfort especially in hot and dry climates. While the comfort is achieved throughout the year satisfactorily for cool and dry weather conditions,

some discomfort prevailed for few months around June / July for Jodhpur (hot and dry) New Delhi (composite) and Ahmadabad (hot and humid). The maximum value of discomfort felt at New Delhi is about 50 PMV-Hours in the month of June / July.

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